

Attorney Docket No. 83091
Customer No. 23523

DECISION FEEDBACK EQUALIZATION PRE-PROCESSOR WITH TURBO EQUALIZER

TO WHOM IT MAY CONCERN:

BE IT KNOWN THAT FLETCHER A. BLACKMON, employee of the United States Government, citizen of the United States of America, resident of Forestdale, County of Barnstable, Commonwealth of Massachusetts, has invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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1 Attorney Docket No. 83091

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3 DECISION FEEDBACK EQUALIZATION PRE-PROCESSOR WITH TURBO EQUALIZER

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5 STATEMENT OF GOVERNMENT INTEREST

6 The invention described herein may be manufactured and used
7 by or for the Government of the United States of America for
8 governmental purposes without the payment of any royalties
9 thereon or therefore.

10
11 BACKGROUND OF THE INVENTION

12 (1) Field of the Invention

13 The present invention relates generally to communications
14 systems and, more particularly, to a high performance iterative
15 and adaptive equalizer/error correction decoder (turbo-
16 equalization) which is especially suitable for use in underwater
17 telemetry.

18 (2) Description of the Prior Art

19 The underwater environment provides numerous difficult
20 obstacles for acoustic communications. The ocean acoustic
21 channel produces large amplitude and phase fluctuations on
22 acoustic signals transmitted therethrough causing temporal,
23 spatial, and frequency dependent fluctuations. Multipath
24 distortion is a significant problem. Underwater regions often
25 experience high and/or variable sound attenuation. Ambient

1 ocean-noise influences the received signal-to-noise ratio and may
2 require high transmission power levels to achieve suitable ratios
3 depending on the conditions.

4 Presently utilized underwater coherent acoustic telemetry
5 systems are often able to transmit M-ary Phase Shift Keying
6 (MPSK) and M-ary Quadrature Amplitude Modulation (MQAM) signals.

7 At the receiver end, these coherent signals may be processed by
8 an adaptive multi-channel decision feedback equalizer (DFE). The
9 DFE is then usually followed by a de-interleaver and an error
10 correction decoder. The overall performance obtained by this
11 type of prior art underwater telemetry system is often
12 acceptable, but is not satisfactory in many situations. The
13 desire for performance improvement has led to higher performance
14 algorithms whose complexity is orders of magnitude greater than
15 the standard decision feedback equalizer (DFE) system followed by
16 de-interleaving and decoding.

17 Turbo equalization and turbo coding may be applied to many
18 detection and decoding problems. Turbo coding involves
19 concatenation of simple component codes with an interleaver so
20 that decoding can be performed in steps using algorithms of
21 manageable complexity. However, the complexity of prior art
22 turbo equalization increases exponentially with the number of
23 channels and/or other factors, thereby making a multichannel
24 telemetry system, as is typically utilized in underwater
25 telemetry systems, highly complex. More particularly, the

1 complexity of the prior art turbo-equalizer grows with channel
2 complexity, modulation level, and spatial and/or time diversity.

3 The complexity of a prior art turbo-equalizer is therefore
4 orders of magnitude greater than the typical DFE structure
5 discussed above.

6 The following U.S. Patents describe various prior art
7 systems that may be related to the above and/or other telemetry
8 systems:

9 U.S. Patent No. 5,301,167, issued April 5, 1994, to Proakis
10 et al., discloses an underwater acoustic communications system
11 that utilizes phase coherent modulation and demodulation in which
12 high data rates are achieved through the use of rapid Doppler
13 removal, a specialized sample timing control technique and
14 decision feedback equalization including feedforward and feedback
15 equalizers. The combined use of these techniques dramatically
16 increases data rates by one and sometimes two orders of magnitude
17 over traditional FSK systems by successfully combating fading and
18 multipath problems associated with a rapidly changing underwater
19 acoustic channel that produce intersymbol interference and makes
20 timing optimization for the sampling of incoming data impossible.

21 U.S. Patent No. 5,559,757, issued September 24, 1996, to
22 Catipovic et al., discloses an underwater acoustic telemetry
23 system that uses spatially distributed receivers with aperture
24 sizes from 0.35 to 20 m. Output from each receiver is assigned a
25 quality measure based on the estimated error rate, and the data,

1 weighted by the quality measure, is combined and decoded. The
2 quality measure is derived from a Viterbi error-correction
3 decoder operating on each receiver. The quality estimator
4 exploits the signal and noise differential travel times to
5 individual sensors. The spatial coherence structure of the
6 shallow-water acoustic channel shows relatively low signal
7 coherence at separations as short as 0.35 m. Increasing receiver
8 spacing beyond 5 m offers additional benefits in the presence of
9 impulsive noise and larger scale inhomogeneities in the acoustic
10 field. Diversity combining, even with only two receivers, can
11 lower uncoded error rates by up to several orders of magnitude
12 while providing immunity to transducer jamming or failure.

13 U.S. Patent No. 6,295,312 B1, issued September 25, 2001, to
14 Susan M. Jarvis, discloses a method and system for communicating
15 in a time-varying medium. A transmitter sends transmissions of
16 the same message data separated in time with respect to one
17 another. A single sensor receives the transmissions. Each
18 received transmission is buffered until all of the transmissions
19 that were sent are received. The buffered transmissions are
20 simultaneously processed via multichannel adaptive equalization
21 only when all of the transmissions that were sent are received.

22 The above cited prior art does not disclose a system whose
23 complexity is similar to that of the prior art decision feedback
24 equalizer followed by a de-interleaver and an error correction
25 decoder, but whose performance is comparable to telemetry systems

1 with much higher orders of complexity. The above cited prior art
2 also does not disclose lower complexity, better performing
3 telemetry system which lowers the complexity associated with
4 turbo-equalization. The solutions to the above described and/or
5 related problems have been long sought without success.
6 Consequently, those skilled in the art will appreciate the
7 present invention that addresses the above and other problems.

8 9 SUMMARY OF THE INVENTION

10 It is a general purpose of the present invention to provide
11 an improved telemetry system.

12 An object of the present invention is an improved underwater
13 communication system for coherent signal transmission.

14 Another object of the present invention is to combine the
15 desirable features of an adaptive feedback equalization (DFE)
16 system with features of a turbo-equalization structure.

17 Yet another object is to provide an augmented high
18 performance iterative receiver algorithm for underwater acoustic
19 telemetry.

20 A feature of one embodiment of the invention combines a
21 decision feedback adaptive equalizer (DFE) with a turbo-equalizer
22 whereby the decision feedback equalizer or variant thereof
23 provides a pre-processing stage for a turbo-equalizer that
24 significantly limits the complexity of the turbo-equalizer.

1 An advantage of the present invention is superior
2 performance as compared to the standard DFE structure.

3 Another advantage is that time or spatial signal diversity
4 can be processed with low complexity within the DFE to provide a
5 single stream of diversity combined symbols which can be
6 processed with a simplified turbo-equalizer construction for use
7 in multichannel transmissions.

8 Yet another advantage of the present invention is that a DFE
9 structure may be utilized therein to take advantage of fractional
10 spacing to help synchronize symbols.

11 Yet another advantage of the present invention is that a DFE
12 structure may be utilized to reduce the extent of the channel
13 response and therefore allow a turbo-equalizer to operate on a
14 much shorter impulse response in order to reduce the complexity
15 thereof.

16 These and other objects, features, and advantages of the
17 present invention will become apparent from the drawings, the
18 descriptions given herein, and the appended claims. However, it
19 will be understood that above listed objects and advantages of
20 the invention are intended only as an aid in understanding
21 certain aspects of the invention, are not intended to limit the
22 invention in any way, and do not form a comprehensive or
23 exclusive list of objects, features, and advantages.

24 Accordingly, the present invention provides a coherent
25 receiver which is operable for use in an underwater telemetry

1 system or for other applications. A coherent receiver in accord
2 with the present invention may comprise one or more elements such
3 as, for instance, one or more data input channels connected to
4 the coherent receiver, and/or a decision feedback equalizer for
5 receiving the one or more data input channels and producing a
6 single stream of pre-processed data at a decision feedback
7 equalizer output, and/or a turbo-equalizer connected to the
8 feedback equalizer output for receiving the single stream of pre-
9 processed data.

10 The coherent receiver may further comprise a plurality of
11 receiver transducers for producing spatially diverse data for the
12 one or more input channels. Alternatively, the coherent receiver
13 may also comprise a single receiver transducer for producing time
14 diverse data for the one or more input channels. In this
15 embodiment, the decision feedback equalizer may also be operable
16 for selectively controlling the total number of the one or more
17 input channels utilized based on error analysis of the diverse
18 data.

19 The coherent receiver may further comprise a training symbol
20 sequence generator and a correlator in communication with the
21 training symbol sequence generator and the decision feedback
22 equalizer wherein the output of the correlator is preferably
23 receivable by the turbo-equalizer.

24 In a preferred embodiment, the turbo equalizer may further
25 comprise an equalizer portion and a decoder portion

1 interconnected for iterative operation. The equalizer portion
2 and the decoder portion may each preferably utilize a maximum a
3 posteriori probability (MAP) algorithm.

4 In operation, the invention comprises a method which may
5 comprise one or more steps such as, for example only, detecting a
6 received signal which may comprise a plurality of data channels,
7 and/or pre-processing the plurality of data channels within a
8 decision feedback equalizer to produce a single output stream of
9 symbol data from the plurality of data channels, and/or post-
10 processing the single output data stream within a single channel
11 turbo-equalizer.

12 The post-processing of the single output data stream may
13 further comprise iteratively equalizing and decoding data from
14 the single output data stream to produce a corrected data output
15 stream and may utilize the MAP algorithm for the steps of
16 iteratively equalizing and decoding.

17 In one embodiment, the method may further comprise
18 mitigating phase jitter in the single output data stream
19 utilizing the decision feedback equalizer.

20 The method may further comprise providing that the received
21 signal comprises a transmitted training symbol sequence, pre-
22 processing the transmitted training symbol sequence to provide a
23 pre-processed training sequence, producing a local training
24 symbol sequence within the receiver, correlating the local
25 training symbol sequence with the pre-processed training sequence

1 to provide channel estimate, and utilizing the channel estimate
2 within the turbo-equalizer.

4 BRIEF DESCRIPTION OF THE DRAWINGS

5 A more complete understanding of the invention and many of
6 the attendant advantages thereto will be readily appreciated as
7 the same becomes better understood by reference to the following
8 detailed description when considered in conjunction with the
9 accompanying drawing, wherein like reference numerals refer to
10 like parts and wherein:

11 FIG. 1 is a block diagram schematic of a presently preferred
12 turbo equalizer in accord with the present invention; and

13 FIG. 2 is a block diagram schematic of a presently preferred
14 DFE pre-processor followed by a reduced complexity turbo-
15 equalizer in accord with the present invention.

17 DESCRIPTION OF THE PREFERRED EMBODIMENT

18 The present invention provides an augmented high performance
19 iterative receiver algorithm for underwater acoustic telemetry.

20 While the prior art turbo-equalization techniques would have
21 been very complex when used to handle underwater telemetry data,
22 which typically comprises multiple channels, a receiver in accord
23 with the present invention combines a decision feedback adaptive
24 equalizer (DFE) with a turbo-equalizer to produce an improved

1 receiver which has a complexity very close to that of a typical
2 prior art DFE system.

3 Referring now to the drawings and, more particularly to FIG.
4 2, there is shown a block diagram schematic for receiver 10 in
5 accord with the present invention. As described hereinbelow in
6 more detail, decision feedback equalizer or variant 12
7 effectively serves as a pre-processor stage for turbo-equalizer
8 14 in a manner that greatly reduces the complexity for use of
9 turbo-equalization techniques as applied to an underwater
10 acoustic telemetry system with multiple channels. Multi-channel
11 input data 13 may include data received from multiple channels
12 such as, for example, spatially diverse data produced from
13 plurality of transducers received from a single transducer but
14 transmitted by a plurality of transducers. Multi-channel input
15 data 13 may also comprise time diversity transmissions such as,
16 for example, use of a single transmitter and/or single receiver
17 wherein the same data is transmitted multiple times. In the case
18 of the single receiver, due to multipath error, each transmission
19 is affected differently by transmission through the underwater
20 environment and when received is treated as a different channel.

21 The multiple channels of data so produced may be processed
22 simultaneously in the same manner as spatially diverse data
23 received by multiple receivers. Alternately, data may be sent to
24 the single receiver and repeated as necessary. Moreover, as
25 discussed below, the data may be sent a selectable number of

1 times so that the data is repeated only often enough for good
2 reception thereby maximizing data transmission rates.

3 There are a number of advantages to the invention. The
4 performance is superior to the prior art DFE structure, but the
5 complexity is comparable. Moreover, many of the benefits of use
6 of a DFE structure are available. Time or spatial diversity can
7 be used with low complexity within the DFE to provide a single
8 output stream of diversity combined symbols. Also, the DFE can
9 take advantage of fractional spacing to help synchronize symbols.

10 The DFE also reduces the extent of the channel response and
11 therefore allows the turbo-equalizer to operate on a much shorter
12 impulse response reducing the complexity.

13 In the past, the turbo principle of operation has been
14 applied to concatenated codes and to many detection and decoding
15 problems. The idea or principle of turbo coding is to build a
16 strong code by concatenation of simple component codes with an
17 interleaver so that decoding can be performed in steps using
18 algorithms of manageable complexity. In turbo equalization, the
19 channel with inter-symbol interference (ISI) including the
20 transmitter and receiver filters might be regarded as a linear
21 finite state machine, serially concatenated to the channel
22 convolutional encoder. In most cases, a serially concatenated
23 system with an interleaver consists of an outer code, an
24 interleaver permuting the outer code words bits, and an inner
25 finite state machine whose input words are the permuted outer

1 code words. There are different examples for serially
2 concatenated systems. One example of such a scheme is the
3 concatenation of a channel encoder and a non-linear modulator
4 with memory, say a continuous phase frequency-shift keying
5 (CPFSK) modulator. Also, concatenation of a convolutional code
6 and a channel with memory can be considered as a serially
7 concatenated system and we may apply the iterative detection
8 algorithms to this system. Iterative detection schemes are sub-
9 optimum detection algorithms with limited complexity for these
10 systems. The optimum decoding algorithms need a trellis with a
11 huge number of states for which we should consider all system
12 memory. For example, for a system with v memories in a
13 convolutional encoder and with an ISI channel with M memories and
14 an interleaver size N , the optimal decoding algorithms need a
15 trellis with $2^{(v+M+N)}$ states. This potential complexity of a turbo
16 equalizer for an underwater telemetry system is greatly reduced
17 in accord with the teachings of the present invention.

18 A block diagram schematic for one embodiment of turbo
19 equalizer 14 which may be utilized in accord with the present
20 invention is shown in FIG. 1. Preferably, soft-input soft
21 output (SISO), maximum a posteriori probability (MAP), iterative
22 algorithms are utilized for both channel equalization and
23 decoding, i.e., MAP Equalizer 16 and MAP Decoder 18. Adaptive
24 decision feedback equalizer (DFE) 12 acts as a pre-processor to
25 pre-condition the symbol data which is passed on to turbo-

1 equalizer 14 as indicated at 20. The multi-channel received
2 input data (spatial and/or time diversity) is processed by
3 adaptive decision feedback equalizer (DFE) 12 which also
4 preferably uses a second order phase locked loop for phase jitter
5 mitigation. DFE 12 thereby provides a single symbol stream at 20
6 given any number of received input channels. In this manner, the
7 present invention thereby limits turbo-equalizer 14 to working on
8 a single channel, thereby greatly reducing complexity.

9 Accordingly, in the system of FIG. 1 and FIG. 2, a sequence
10 of synchronized phase compensated values are produced by DFE 12,
11 as indicated at 20, as an input in turbo equalizer 14. MAP
12 equalizer 16 delivers Log values $L^E(u;0)$ about coded bits. After
13 de-interleaving, the channel MAP decoder delivers Log values $L^P(\hat{u})$
14 about information bits and Log values $L^P(c;0)$ about coded bits.
15 Soft-values, preferably in the form of log-likelihood ratios
16 (LLR) values, at the output of MAP decoder 18 consist of an
17 extrinsic and an intrinsic part. The extrinsic part is the
18 incremental information about the current bit obtained through
19 the decoding process from all the other bits in the block. The
20 extrinsic part can be calculated by subtraction of the LLR values
21 as indicated at 19. The extrinsic part, as indicated at 22, is
22 interleaved and fed back to MAP equalizer 16 where the extrinsic
23 part is used as a priori information $L^E(u;1)$ in the new decoding
24 iteration. In a preferred embodiment, the outputs as determined
25 by the iterative processing, which may be hard outputs or soft

1 outputs (which are easily converted to hard outputs), are
2 produced at output 28.

3 DFE 12 also has sparsing capability. That is to say that
4 time delayed multipath or channel effects are mitigated by DFE
5 12. Multipath mitigation has the effect of shortening the
6 channel response and limiting the number of important
7 contributing channel coefficients that need to be used by turbo-
8 equalizer 14 thereby lowering complexity. Also, the data from
9 the DFE 12 is fractionally spaced, i.e. 2 samples per symbol,
10 which aids in symbol synchronization for turbo-equalizer 14. The
11 second order phase locked loop structure in the DFE allows for
12 phase jitter mitigation thereby removing the need for estimation
13 of this error from turbo-equalizer 14.

14 The reduced channel estimate for the turbo-equalizer can be
15 obtained by using correlator 26 to cross-correlate the training
16 symbol sequence produced by generator 24 with the corresponding
17 received output symbols from DFE 12 which are the received
18 version of the same information. The reduced channel response
19 at 27 is applied to turbo-equalizer 14.

20 Turbo-equalizer 14 is able to apply the iterative MAP
21 equalization and iterative MAP decoding operating principles as
22 discussed above to correct residual equalization symbol errors
23 that still remain after DFE 12 which acts as a pre-processor
24 stage in hard output 28.

1 One embodiment of the present invention may also be utilized
2 to increase the data rate throughput of prior art time diversity
3 receivers. The present invention is operable to utilize or
4 increase/decrease the number of time diversity data channels,
5 i.e., the number of times the data is resent, in response to
6 analyzing the data packet errors. In this embodiment, if errors
7 are present, only then a subsequent copy of the data packet is
8 resent and/or the number of times the transmitter resends the
9 data packet is controlled whereby the receiver combines the data
10 using time diversity equalization as taught in the prior art
11 discussed hereinbefore. If the data packets are error free,
12 there is no need for additional time diversity or increased time
13 diversity combining. Therefore, on average, the data rate can be
14 increased beyond that possible with constant time diversity
15 processing. In fact, the present invention may or may not be
16 utilized with multichannel data depending on an ongoing analysis
17 of data packet errors and then determining the number of channels
18 required so that the transmitter produces repeated data packets
19 only as needed to obtain accurate reception.

20 In summary, the performance improvement of receiver 10 is
21 due to using the turbo-equalization technique to clean up
22 residual error that is left behind by pre-processing performed by
23 DFE 12. Time and/or spatial diversity can be used with low
24 complexity within DFE 12 to provide a single stream of diversity
25 combined symbols. Also, DFE 12 can take advantage of fractional

1 spacing to help synchronize symbols. The use of outputs from DFE
2 12 for the training symbol sequence reduces the extent of the
3 channel response and therefore allows turbo-equalizer 14 to
4 operate on a much shorter impulse response thereby reducing the
5 complexity. DFE 12 preferably utilizes a second order phase
6 locked loop to mitigate channel induced phase jitter. This
7 technique can be used to mitigate channel estimation error in
8 turbo-equalizer 14. The new channel estimate for turbo-equalizer
9 14 may be provided by the correlation of the known training
10 symbol sequence and DFE 12 unquantized symbol output.

11 Many additional changes in the details, components, steps,
12 algorithms, and organization of the system, herein described and
13 illustrated to explain the nature of the invention, may be made
14 by those skilled in the art within the principle and scope of the
15 invention. It is therefore understood that within the scope of
16 the appended claims, the invention may be practiced otherwise
17 than as specifically described.